

Governor System for General Purpose Engine Using Adaptive Control Theory

Tomoki FUKUSHIMA*
Yoshihisa SHINOGI*

Hayato MATSUDA*
Yoichi TANIGUCHI*

ABSTRACT

General purpose engines are required to keep the engine speed constant, and are therefore equipped with governor mechanisms. However, the engines are applied to various applications, and the dynamic characteristics of the controlled engine changes according to different operating conditions. So it is necessary for a conventional mechanical governor to change the spring rate and tune the idle speed; similarly, gains must be tuned in electronic governors using PID control. To enhance robustness, an adaptive control system that uses a self-tuning regulator has been constructed. Applying elliptical gears to the mechanism for driving the throttle valve, it was possible to realize both high resolution near the closed position and a reduction in operating time of the throttle valve.

1. Introduction

In automobiles and on motorcycles, people estimate conditions using the speedometer and their five senses and then use the throttle (accelerator pedal) for control. In comparison, products with general purpose engines, most notably the small single cylinder engines (in generators, lawn mowers, tillers, snow throwers, water pumps, etc.) have a mechanism that automatically adjust the throttle opening of the carburetor, either because it is not possible for a person to respond fast enough to sudden load changes or for unattended operation. This is a mechanism for keeping the engine speed constant. Many products use mechanical feedback control which applies James Watt's centrifugal force governor mechanism⁽¹⁾ such as the one shown in Fig. 1. This mechanism detects changes in engine speed using the centrifugal force of a counterweight, and a linkage adjusts the throttle opening of the carburetor. The throttle opening becomes steady at where the centrifugal force and governor spring are balanced. However, there is mechanically a difference

in engine speed between idle and when a load is applied.

In recent years, use of inexpensive high performance microprocessors has enabled the introduction of governors that are electronic (hereinafter; electronic governors) as generators, instead of mechanical governor mechanisms. The electronic governors drive the throttle valve shaft using a motor and converge engine speed to a target value by PID control, etc. However, as a governor for general purpose engines where dynamic characteristics of the controlled object change, due to the fact that the engines are used for several different applications, and the environmental use conditions such as temperature and pressure change, it is not sufficiently robust and gain adjustments adapted to changes in dynamic characteristics are required. In the present research, an electronic robust governor using an adaptive control theory has been developed, which has used Self-tuning Regulator control^{(2),(3)} (hereinafter, STR control) for changes to dynamic characteristics of the controlled object in order to control the engine speed of the small-single cylinder engines.

* Asakahigashi R&D Center

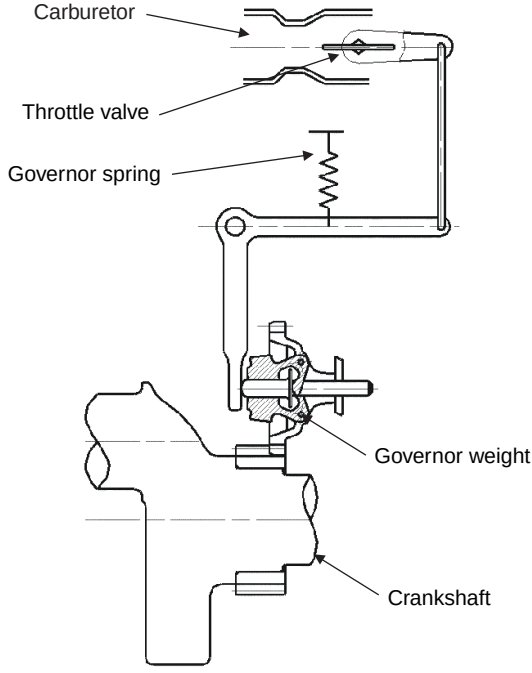


Fig. 1 Centrifugal type governor

2. Implementation of STR Control

2.1. Engine Modeling

Figure 2 shows a simplified engine model where throttle opening is used as an input. Considering the block diagram of a general purpose base engine that uses a carburetor, mass air flow G_a and mass fuel flow G_f are determined by the throttle opening θ_{th} and engine speed NE when the air fuel ratio is fixed. A mean effective pressure P_{mi} generated by combustion of the intake mixture is converted to engine speed by the crank linkage system. The engine load characteristics, connected to this crank linkage system of general purpose engines, differ with the engine application (for generators, lawn mowers, tillers, snow throwers, water pumps, etc.). Even when the engine is used on the same application, the load characteristics differ with the moment of inertia of the attachment. In order to control an electronic governor, the throttle opening angle θ_{th} is selected as the input and engine speed NE selected as the output, with the area surrounded by dashed lines is used as a single block model for the controlled object.

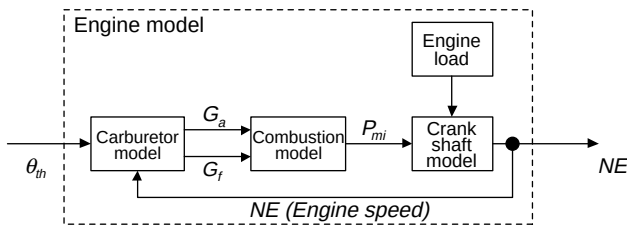


Fig. 2 Block diagram of engine model

A step response of the engine speed relative to step input of the throttle valve is shown in Fig. 3. With the premise of performing adaptation control using the ARX (Auto-Regressive Exogenous) model⁽⁴⁾, a minimum square model (Equation 1), with throttle opening θ_{th} as the input u and engine speed NE as the output y , modeling was performed while focusing on the order and lag-type.

$$A(q^{-1})y(k) = q^{-1}B(q^{-1})u(k) + w(k) \quad (1)$$

$$A(q^{-1}) = 1 + a_1q^{-1} + \dots + a_nq^{-n} \quad (2)$$

$$B(q^{-1}) = b_0 + b_1q^{-1} + \dots + b_mq^{-m} \quad (3)$$

$a_1 \dots a_n, b_0 \dots b_m$: Model parameters

$w(k)$: White noise

In Eq. (1), with the target engine speed defined as y_m the output error is calculated using the following equation.

$$e_1(k) = y_m(k) - y(k) \quad (4)$$

The control object is automatically adjusting the throttle opening u , the input, allowing the engine speed y , the output of the controlled object, to become equivalent to the target engine speed y_m . Here, the load fluctuation is a primary unknown parameter. In addition, the whole parameters of the engine combustion model, including the load, are estimated as the unknown parameter by sequential calculation.

2.2. Controller Design

With the introduction of the Diophantine equation⁽⁵⁾ and configuring Eq. (1) in the following manner, variance of the output error can be minimized, enabling achievement of the control object.

$$u(k) = \frac{1}{b_0} \{y_m(k+1) - \bar{\theta}^T \bar{\zeta}(k)\} \quad (5)$$

Here,

$$\bar{\theta}^T = [b_1 \dots b_m, h_0 \dots h_{n-1}] \quad (6)$$

$$\bar{\zeta}(k) = [u(k-1) \dots u(k-m), y(k) \dots y(k-n+1)] \quad (7)$$

However, in the actual system, as the parameter is unknown, sequential estimation is performed using parameter estimation law below.

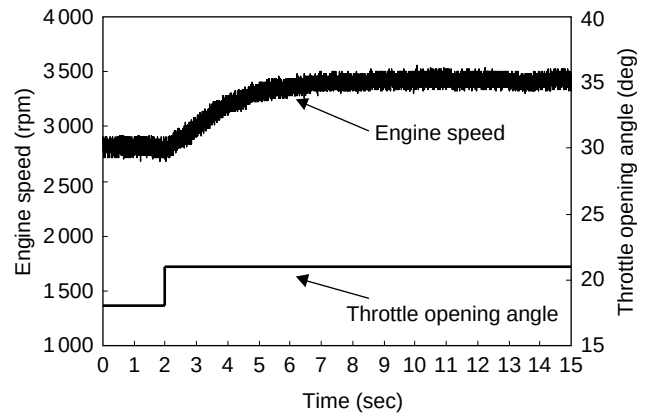


Fig. 3 Step response

$$\hat{\theta}(k) = \hat{\theta}(k-1) - \Pi(k-1) \zeta(k-1) \varepsilon_1(k) \quad (8)$$

$$\Pi(k) = \frac{1}{\lambda_1(k)} \Pi(k-1) - \frac{1}{\lambda_1(k)} \left[\frac{\lambda_2(k) \Pi(k-1) \zeta(k-1) \zeta^T(k-1) \Pi(k-1)}{\lambda_1(k) + \lambda_2(k) \zeta^T(k-1) \Pi(k-1) \zeta(k-1)} \right] \quad (9)$$

Here,

$$\theta^T = [b_0, \bar{\theta}^T] \quad (10)$$

$$\zeta^T(k) = [u(k), \bar{\zeta}^T(k)] \quad (11)$$

Here $0 < \lambda_1(k) \leq 1$, $0 \leq \lambda_2(k) < \lambda_1(k)$, $\Pi(0) = \Pi^T(0) > 0$

If the unknown parameter converges to the true value, the system becomes the minimum variance control using the configuration of Eq. (5). Therefore, a robust controller for a general purpose engine speed governor with respect to dynamic characteristic fluctuations can be attained.

3. Mechanism Characteristics

An outline form of the electronic governor mechanism installed on iGX440⁽⁶⁾ is shown in Fig. 4.

The following items were considered in tandem with the application of an electronic governor to a general purpose engine that is used in several applications and various environments.

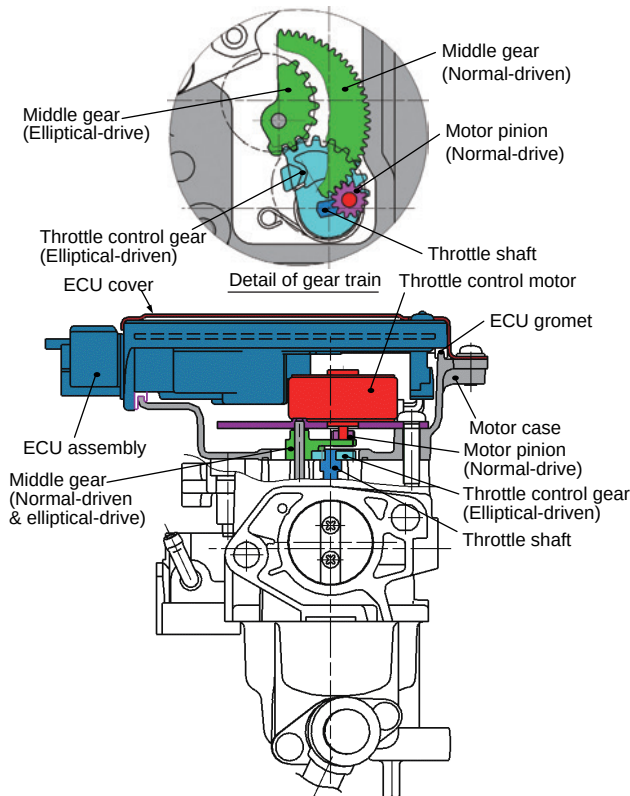


Fig. 4 Carburetor assembly

Table 1 Characteristics of actuator

	Stepping motor	DC motor	Solenoid
Control method	Open loop	Feedback	Feedback
Position control	Number of pulse	Feedback by position sensor	Feedback by position sensor
Speed control	Pulse rate	PWM control	Current control
Power supply	Constant voltage	PWM control	Current control
Life	Bearing life (long life)	Brush life (short life)	Bearing life (long life)

- Feasibility of operating without a battery.
- Reducing sensors to a minimum to help achieve reliable durability.
- Use of a simple drive circuit enabling use of a compact ECU.

Stepper motors, DC motors, and solenoids were considered as the actuator for the throttle drive. Table 1 shows characteristics for each of these actuator types. Accordingly, in order to have stop position control without requiring sensors, a simple drive circuit, and long life, a stepper motor was selected as the actuator for driving the general purpose engine throttle.

However, due to all the various characteristics required of a general purpose engine, just applying a stepper motor is insufficient and the following technical methods have additionally been applied.

- Non-linear reduction to satisfy required characteristics of the throttle
- Compact layout for integral construction ECU and carburetor
- Cost and size minimization of electronics in order to maintain weather and dust resistance

Details concerning these three points are described below.

3.1. Non-linear Reduction Mechanism

The relationship between throttle opening θ_{th} and mass air flow G_a controlled by a butterfly throttle valve is shown in Fig. 5. Independent of the engine speed, within the limits of $\theta_{th} < 30$ degrees, the amount of fluctuation of G_a with respect to the throttle opening is sensitive; therefore, in order to stabilize engine speeds when in idle and slight throttle opening states, control resolution must be fine.

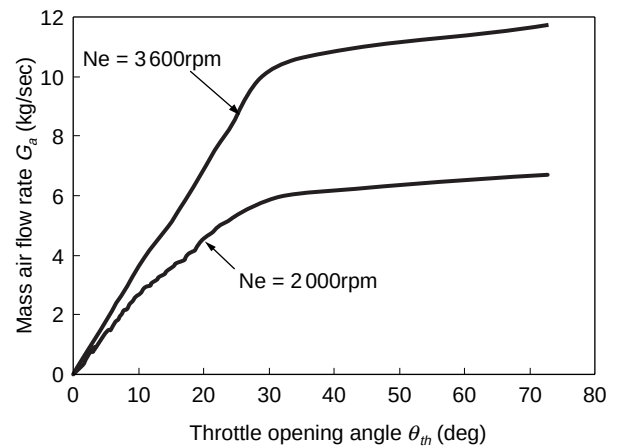


Fig. 5 Mass air flow rate

A Permanent Magnet type stepper motor (hereinafter; PM type stepper motor) has been selected for use in this mechanism as the actuator to control the throttle valve. The angle control capability of a PM type stepper motor is determined by the pitch of the rotor magnet and pole stator and there are physical limits with the enhancing resolution of the motor itself. Therefore, enhancement of resolution is generally provided by gear reduction. If the reduction gear train is formed using normal gears and resolution is set fine to meet slight opening requirement characteristics, throttle opening and closing speed is reduced due to the stepper motor characteristics involved.

General purpose engines frequently have 0% to 100% and 100% to 0% sudden load fluctuations. In order to enhance the ability to minimize engine speed fluctuations during load fluctuations, it is necessary to increase the throttle opening and closing speed.

Increasing the speed of input pulses is a method for increasing motor speed; however, as shown in Fig. 6, torque generated by the motor is reduced, leading to a reduction in surplus torque relative to that required to drive the throttle, which is itself a cause for loss of synchronization. On the other hand, if resolution is set loosely, matching the requirements of a large throttle opening, resolution at slight opening is insufficient and can cause hunting.

In order to allow for these conflicting requirements, elliptical gears⁽⁷⁾ have been utilized. Figure 7 shows a linkage that uses elliptical gears.

With θ_m , θ_{th} as the centers of the ellipses, and respective focus F_m , F'_m , F_{th} and F'_{th} of gears of the same shape with long diameter $2a$, and short diameter $2b$ and with F_m and F_{th} as rotational axes, $|A_m F_m| = \rho_m$, $|A_{th} F_{th}| = \rho_{th}$ and θ_m , θ_{th} as the rotation angles.

$$\rho_m = \frac{r}{1 + \varepsilon \cos \theta_m} \quad (12)$$

$$\rho_{th} = \frac{r}{1 - \varepsilon \cos \theta_{th}} \quad (13)$$

$$\rho_m + \rho_{th} = 2a \quad (14)$$

$$\text{However, } r = \frac{b^2}{a}, \varepsilon = \frac{\sqrt{a^2 - b^2}}{a}$$

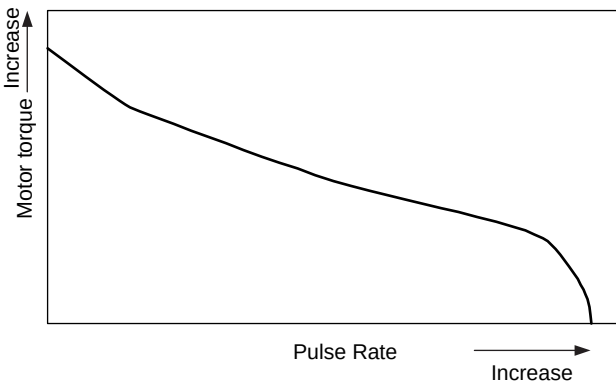


Fig. 6 Characteristics of motor torque

Therefore,

$$\theta_{th} = \cos^{-1} \left\{ \frac{(1 + \varepsilon \cos \theta_m) \cdot (2a - r) - r}{[2a \cdot (1 + \varepsilon \cos \theta_m) - r] \cdot \varepsilon} \right\} \quad (15)$$

The relationship of θ_m and θ_{th} with $\varepsilon = 0.25, 0.425$, and 0.65 is shown in Fig. 8.

When the elliptical gear θ_m rotates through a differential angle $d\theta_m$, θ_{th} rotates through an angle $d\theta_{th}$. This leads to the following relationship becoming equal.

$$\rho_m \cdot d\theta_m = \rho_{th} \cdot d\theta_{th} \quad (16)$$

However, as $\frac{d\theta_m}{dt} = \omega_m$ and $\frac{d\theta_{th}}{dt} = \omega_{th}$ rewriting of Eq. (16) becomes

$$\omega_{th} = \frac{\rho_m}{\rho_{th}} \omega_m \quad (17)$$

With ω_m operating at uniform speed it can be seen that when $\rho_m < \rho_{th}$, $\omega_m > \omega_{th}$ and if $\rho_m > \rho_{th}$, $\omega_m < \omega_{th}$. In other words with O_m as the drive gear and O_{th} as the driven gear (throttle drive), with the gears set in full closed position as shown in Fig. 7, the amount of change of θ_{th} with respect to θ_m near where the throttle is fully closed is insensitive; however, the amount of change of θ_{th} with respect to θ_m near wide open throttle is more sensitive. This characteristic is determined by the eccentricity ε of the ellipse. The

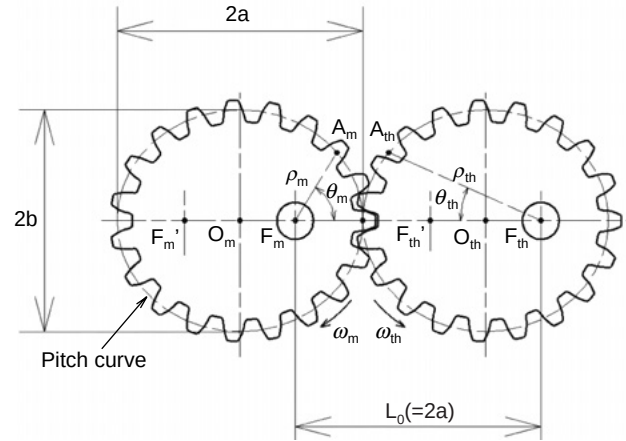


Fig. 7 Elliptical gear train

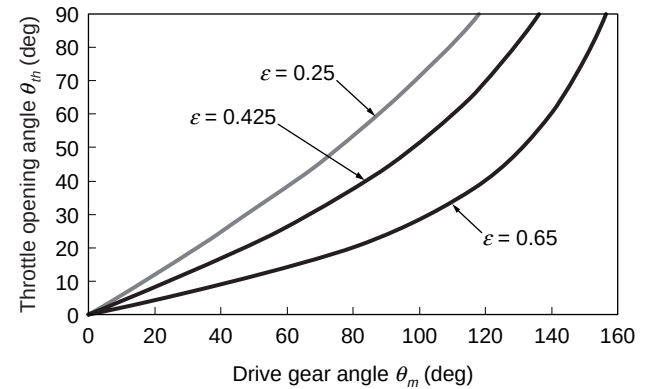


Fig. 8 Characteristics of angle with difference in elliptical gear eccentricity

relationship of $d\theta_{th}/d\theta_m$ with $\epsilon = 0.25, 0.425$, and 0.65 is shown in Fig. 9. It can be seen that increasing the value of ϵ leads to an enhancement in resolution for low throttle valve openings.

The calculation of resolution with respect to the throttle opening with ϵ at maximum permissible with a given layout is shown in Fig. 10. By using a non-linear resolution mechanism such as this, a linear relationship between motor step pulse and mass air flow G_a such as shown in Fig. 11 is achieved. If the non-linear relationship is corrected mechanically, linearization processing using the control system is no longer needed.

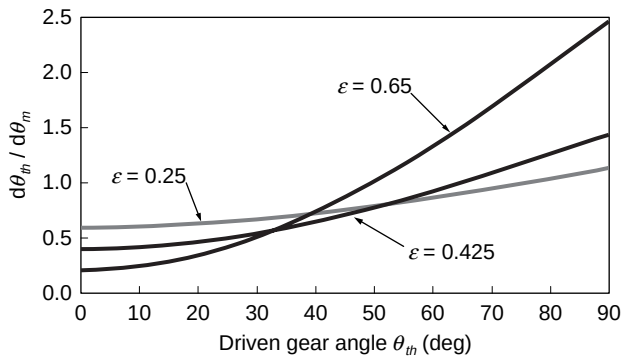


Fig. 9 Characteristics of angular velocity with difference in elliptical gear eccentricity

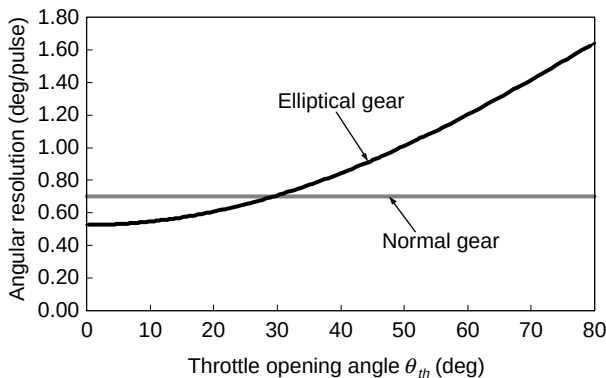


Fig. 10 Characteristics of angular resolution

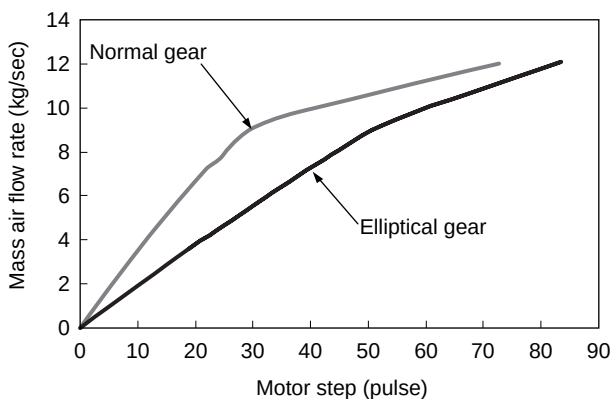


Fig. 11 Relationship between motor step and mass air flow rate (Engine speed = 3600rpm)

A comparison of a normal gear reduction with minimum resolution equivalent to the resolution curve shown in Fig. 10 and the number of steps needed from where the throttle is fully closed to it becomes wide open is shown in Fig. 12. The number of steps used for an elliptical gear mechanism is 35% less than the number used for a normal gear.

In conjunction with use of an elliptical gear mechanism, the relationship between throttle drive torque requirements and actual throttle drive torque is shown in Fig. 13. Because the throttle drive torque is inversely proportional to resolution, elliptical gear mechanism throttle drive torque is large when the throttle is closed and becomes smaller when the throttle is wide open. Throttle torque was designed to be at least 1.5 times that of maximum throttle drive torque requirements. During sudden accelerations or decelerations, where the throttle suddenly moves from being wide open to one where it becomes all the way closed, a larger than normal negative pressure is applied to the throttle valve causing resistance to the movement of the throttle shaft. The fact that maximum torque of this mechanism is generated where the throttle valve is closed contributes to increased toughness with respect to the resistance of the throttle shaft movement.

3.2. Compact Layout

As a general purpose engine, it is necessary to position the ECU and electronics for the throttle control mechanism, etc. so as not to increase overall dimensions. The motor and gear case combination is placed on top of the carburetor and the motor and reduction gears are placed inside the silhouette of the carburetor. Through centralizing the placement of large components on the circuit board in the ECU on the motor case, compared to the conventional method

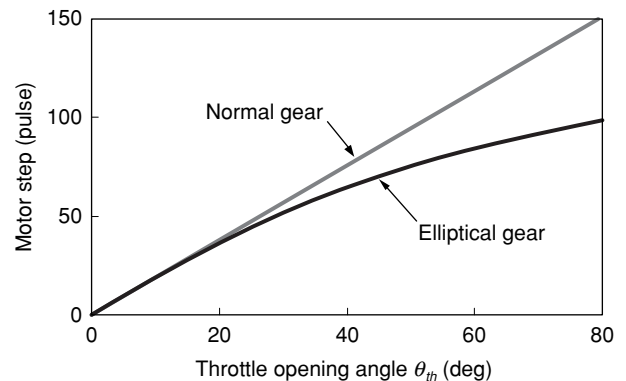


Fig. 12 Relationship between throttle opening angle and motor step

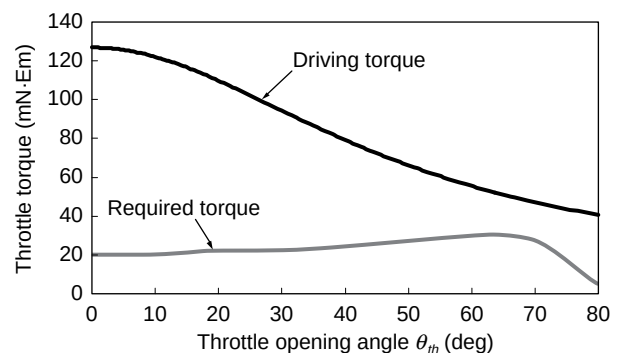


Fig. 13 Characteristics of throttle torque

of molding an ECU in a uniform depth case, the overall height has been reduced by 16 mm.

Furthermore, as the connector that connects the ECU and motor is placed in the same case, this contributes to a reduced connector size, enabling a simplification of the wiring, and contributing to a compact layout.

3.3. Water and Dust Resistance

As shown in Fig. 4, sealing is provided by an O-ring that is placed between the aluminum motor case and the carburetor and by a grommet between the ECU and motor case, making the motor case and ECU air tight. As electronics are placed inside of these units, water resistance and dust resistance thus become unneeded for individual electronic parts, enabling a reduction in size and cost.

4. Installation in Equipment Results

With a test engine GXV160 (Table 2) installed in a lawn mower, Fig. 14 shows results comparing governor characteristics between its use in a conventional mechanical governor and in an adaptive control type electronic governor. The conventional mechanical governor has steady state error, where the engine speed fluctuates depending on the load. With respect to this point, when using an adaptive control type electronic governor, it can be seen that engine speed is uniform, independent of the load.

In addition, a test engine GX160 (Table 2) installed on a cylindrical power generator was equipped with an elliptical gear as shown in Fig. 10, and with a normal circular gear, and their idle stability were compared. For this comparison, the same STR control forming an electronic governor was used, the electric load was set to no load and the target engine speed set to 1 400 rpm. Results for the use of the elliptical gear mechanism are shown in Fig. 15 and results where the normal circular gear was used are shown in Fig. 16. Through the use of the elliptical gear mechanism, as compared to the use of a normal circular gear mechanism, idle stability has been enhanced.

An iGX440 engine that uses an adaptive control type electronic governor system is shown in Fig. 17. With this engine installed on a cylindrical power generator, output power characteristics relative to different engine speeds are shown in Fig. 18. The convergence capability of engine speed fluctuations during rated load intermittent

Table 2 Test engine specifications

Model	GX160	GXV160
Type	Air-cooled, 4-stroke, single-cylinder gasoline (OHV)	Air-cooled, 4-stroke, single-cylinder gasoline (OHV)
Displacement (cm ³)	163	163
Dimensions L × W × H (mm)	304 × 362 × 335	415 × 359 × 354
Dry weight (kg)	15	14.6
Bore × Stroke (mm)	68 × 45	68 × 45
Max. power (kW / rpm)	4.1 / 3600	4.1 / 3600

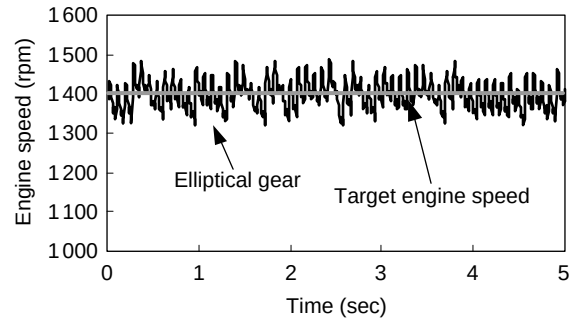


Fig. 15 Idle characteristic with elliptical gear

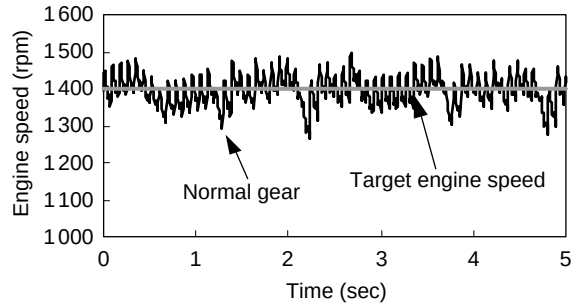


Fig. 16 Idle characteristic with normal gear

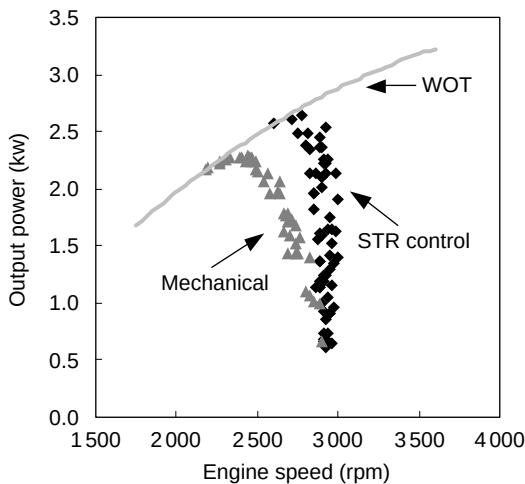


Fig. 14 Dynamic characteristic of governor



Fig. 17 External view of iGX440

operation (from 100% to 0% and 0% to 100%) is shown in Fig. 19.

As shown in Fig. 18, engine speed fluctuation from idle to that of a wide open throttle for an arbitrary engine speed setting was held to within 2%, demonstrating that the strength of an electronic governor, high engine speed stability, was obtained. In addition, as shown in Fig. 19, engine speed fluctuations relative to the set speed during rated load intermittent operation show a favorable convergence capability of 8%, which is within the original goal of 10%. Both stability of engine speed for no loads and convergence of engine speed during load fluctuations have been achieved.

Furthermore, an adaptive control type electronic governor was installed in commercialized products (lawn mowers, snow throwers, pressure washers, etc.) to perform practical durability testing for confirmation. Tuning was not required for the individual products where favorable operation characteristics were obtained from the beginning through to the end of the durability testing verifying the validity of this system.

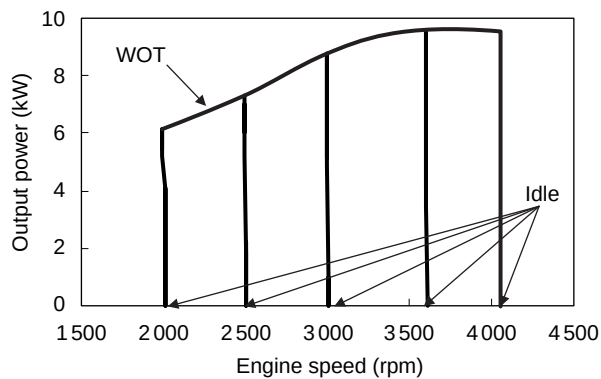


Fig. 18 Static performance of governor

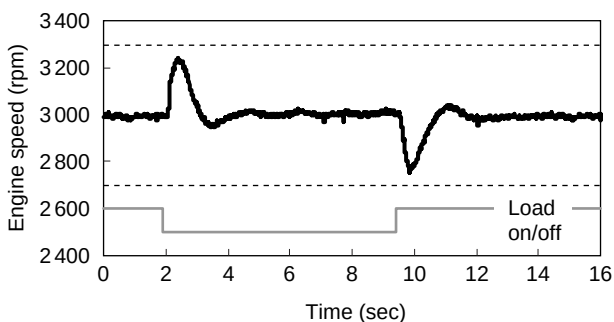


Fig. 19 Dynamic performance of governor
(Target engine speed = 3000rpm)

5. Conclusion

Through applying adaptive control and a non-linear gear mechanism to the governor of a general purpose engine, the following features have been achieved.

- (1) A robust governor relative to fluctuations of dynamic characteristic of the engine, the controlled object, has been developed, allowing use in a general purpose engine, for which applications are unlimited.

- (2) The realization of both a high resolution near the closed position and a reduction in operating time of the throttle valve made it possible to control the engine from idle condition to sudden load change condition.
- (3) Through linearization of the relationship between motor step and mass air flow, linearization of the input signal in control calculations becomes unnecessary, leading to a simplified control system.

References

- (1) Gomi, T.: Nainen Kikan, p.214-215 (1985) (in Japanese)
- (2) Terao, M., Kanai, K.: Robust Adaptive Control, p. 109-113 (1993)
- (3) Omatsu, S., Yamamoto, T.: Self Tuning Control, p. 3-4 (1996)
- (4) Adachi, S.: Seigyo no tameno System Dotei, p. 55-64 (1996) (in Japanese)
- (5) Goodwin, G. C., Long, R. S.: Generalization of Results on Multivariable Adaptive Control, IEEE Trans., AC-24-6, p. 1241-1245 (1980)
- (6) Ito, K., Honda, S., Saito, T., Kurata, M., Naoe, G.: Development of Electronically Controlled Multi-purpose Engine iGX440, Honda R&D Technical Review, Vol. 17, No. 2, p. 44-51 (2005)
- (7) Katori, H.: Hienkei Haguruma no Sekkei Seisaku to Ouyou, p. 7-34 (2001) (in Japanese)

■ Authors ■



Tomoki FUKUSHIMA



Hayato MATSUDA



Yoshihisa SHINOBI



Yoichi TANIGUCHI